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Evaluation of chemical amendments to control phosphorus losses from dairy slurry.

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RUNNING HEAD TITLE:

Chemical amendments to control phosphorus

25 **Abstract**

26

27 The aim of this paper is to identify chemicals with the potential to reduce P losses from
28 agricultural grassland arising from the land application of dairy cattle slurry. It also aims
29 to identify optimal application rates and to estimate associated costs. The cost of
30 chemical amendments was estimated based on cost of chemical, chemical delivery,
31 addition of chemical to slurry, volume increases during slurry agitation, and slurry
32 spreading costs. First, batch tests were carried out to identify appropriate chemical and
33 phosphorus sorbing materials (PSMs) to be considered as potential amendments to
34 control P in runoff from dairy cattle slurry. Then, the best seven treatments were
35 examined in a novel agitator test. Optimum application rates were selected based on
36 percentage removal of dissolved reactive phosphorus (DRP) in overlying water and the
37 estimated cost of amendment. At optimum application rates, alum reduced the DRP in
38 overlying water by 94%, aluminium chloride (AlCl_3) by 92%, ferric chloride (FeCl_3) by
39 88%, lime by 81%, aluminium water treatment residuals (Al-WTR; sieved to $<2\text{mm}$) by
40 77%, Al-WTR sludge by 71%, flyash by 72%, and flue gas desulphurisation by-product
41 by 72%. Alum was the most cost-effective chemical amendment, and was capable of
42 greater than 90% reduction in soluble P in overlying water. The optimum FeCl_3
43 amendment was less expensive, but not quite as effective. AlCl_3 and lime are expensive,
44 and despite the attractiveness of using PSM, those examined were not cost effective at P
45 reductions of greater than 85%.

46

47 *Keywords:* Water treatment residual; alum; aluminium chloride; ferric chloride; lime; flue
48 gas desulphurisation by-product; flyash.

49

50 **Introduction**

51

52 Repeated application of organic and mineral fertilizer causes soil test phosphorus (STP)
53 to build up in the soil and, during rainfall events, may cause nutrients to be released to
54 surface runoff (Hao et al., 2008). Runoff from grassland pastures and meadow fields
55 following slurry application can result in incidental phosphorus (P) losses and has the
56 potential to transport nutrients to surface water (Smith et al., 2001a). This may result in
57 eutrophication of rivers and fresh water lakes.

58

59 Chemical amendments can either be added directly to the manure before land application
60 (Moore et al., 1998), spread on the ground before manure application (McFarland et al.,
61 2003), or incorporated into the ground (Novak and Watts, 2005).

62

63 Aluminium (Al) compounds are the preferred amendment, as calcium phosphate minerals
64 are not as stable (Moore et al., 1998), and ferrous compounds can break down in acidic
65 soil conditions (Smith et al., 2001b). To date, work involving alum addition to dairy
66 cattle slurry has been largely limited to laboratory batch studies.

67

68 Novak and Watts (2005) incorporated aluminum water treatment residuals (Al-WTR)
69 into the upper 15 cm of topsoil at a 1-6% soil volume. This lowered water extractable P
70 (WEP) in the soil by between 45% and 91% after an 84-d incubation period.

71

72 Coal combustion by-products have potential to mitigate P loss from soil following
73 manure application (Dao, 1999). Stout et al. (1998) reported that by blending flyash with
74 soil at 0.01 kg/kg soil, Mehlich-III P (M3-P) and WEP were lowered by 13% and 71%,
75 respectively. Flue gas desulphurisation (FGD) by-product, applied at 0.01 kg/kg soil,
76 lowered M3-P by 8% and WEP by 48%.

77

78 McGrath et al. (2010) examined the sorption and retention mechanisms of several PSMs
79 and found the degree of sorption to be strongly influenced by the solution pH, buffer
80 capacity, and ionic strength of amendments.

81

82 Present agricultural practice is governed by The European Communities (Good
83 Agricultural Practice for Protection of Waters) Regulations 2009 (S.I. No. 101 of 2009),
84 drafted to comply with the Nitrates Directive (91/676/EEC; EEC, 1991). The Water
85 Framework Directive (WFD; 2000/60/EC, OJEC, 2000) recommends research and
86 development of new pollution mitigation measures to achieve the 2015 target of surface
87 and groundwaters of 'good status'. Therefore, there is potential that chemical treatment of
88 dairy cattle slurry maybe used to control P in Ireland.

89

90 The 'agitator test' is a simple and effective test that has been used to investigate the
91 release of P from soil (Mulqueen et al., 2004). This test was chosen to evaluate the
92 effectiveness of the chemical amendments in reducing incidental soluble P loss from
93 slurry as it is more realistic than traditional batch-type experiments.

94

95 The objectives of this study were to use the agitator test: (i) to determine if there is
96 potential use of chemical amendments to reduce P loss from the soil surface after land
97 application of dairy cattle slurry; (ii) to identify optimum amendment application rates;
98 (iii) to evaluate the feasibility of these treatments, and to estimate the cost of each
99 treatment.

100

101 **Materials and Methods**

102

103 **Soil preparation and analysis**

104

105 The soil samples used in this study were taken from a local dry stock, extensively
106 operated farm with undulating terrain. 120-mm-high, 100-mm-diameter aluminium
107 coring rings were used to collect the samples. The grass was left intact and all soil cores
108 were stored at 11°C in a cold room prior to testing. All agitator tests were carried out
109 within 21 d of sample collection and tests were conducted in triplicate (n=3).

110

111 Soil samples – taken from the same location - were air dried at 40 °C for 72 hr, crushed to
112 pass a 2 mm sieve, and analysed for P using MP-3 extracting solution (Mehlich, 1984)

113 and Morgan's P using Morgan's extracting solution (Bourke et al., 2007). Soil pH was
114 measured in triplicate after Bourke et al. (2007). Shoemaker-McLean-Pratt (SMP) buffer
115 pH was determined and the lime requirement (LR) of the soil was calculated after Pratt
116 and Blair (1963). Particle size distribution (PSD) was determined using B.S.1377-2:1990
117 (BSI, 1990a). Organic content of the soil was determined using the loss of ignition (LOI)
118 test (B.S.1377-3; BSI, 1990b).

119

120 **Slurry sampling and analysis**

121

122 Dairy cattle slurry from replacement heifers was used in this study. The slurry tanks were
123 agitated until the slurry was homogenized, and slurry samples were collected in 10-L
124 drums and transported to the laboratory. Slurry samples were stored at 4°C until
125 immediately prior to the start of the agitator test. Slurry pH was determined using a pH
126 probe (WTW, Germany) at 0 hr and 24 hr. The WEP of slurry was measured after 24 hr
127 after Kleinman et al. (2007). The total phosphorus (TP) of the dairy cattle slurry was
128 determined after Byrne (1979). Potassium (K) and magnesium (Mg) were analyzed using
129 an On varian Spectra 400 Atomic Absorption instrument, and analyses for nitrogen (N)
130 and P were carried out colorimetrically using an automatic flow-through unit.

131

132 **Analyses of PSMs**

133

134 The pH of the PSMs was measured in triplicate using 2:1 deionised water: dry
135 amendment ratio after Bourke et al. (2007). In the case of the Al-WTR sludge, it was

136 possible to measure pH of the sludge with a pH probe. Dry matter (DM) content was
137 determined by drying at 40°C for 72 hr. Total metal and P of the PSMs was measured by
138 'aqua regia' digestion using a Gerhard Block digestion system (Cottenie & Kiekens,
139 1984), which is described by Fenton et al. (2009). WEP of the PSMs was determined
140 after Dayton and Basta (2001).

141

142 **Slurry treatment**

143

144 Tests were carried out to determine the effectiveness of various chemical amendments to
145 treat the dairy cattle slurry. The best seven P-sorbing amendments were examined in the
146 agitator test; these were: industrial grade alum (8% Al_2O_3 , $\text{Al}_2(\text{SO}_4)_3 \cdot n\text{H}_2\text{O}$); laboratory
147 grade aluminium chloride ($\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$); FeCl_2 ; burnt lime ($\text{Ca}(\text{OH})_2$); Al-WTR, sieved
148 to less than 2 mm (Al-WTR-1); Al-WTR homogenised sludge (Al-WTR-2); flyash; and
149 FGD (Table 1). Chemical amendments were applied based on Al:TP stoichiometric rate,
150 and PSMs were applied based on a kg/kg weight basis (slurry dry matter). The Al-WTR
151 was obtained from a local water treatment plant (WTP) and the coal combustion by-
152 products were provided by the Electricity Supply Board (ESB) at Moneypoint, Co. Clare.

153

154 The pH of the amended slurry was measured prior to application at $t=0$ hr. Samples were
155 taken to determine DM and WEP of the amended slurry (after Kleinman et al., 2007).

156 Slurry and amended slurry were applied to surface of the grassed soil at a rate equivalent
157 to 40 kg TP/ha (50 m^3 slurry/ha). For each treatment, slurry samples ($n=3$) with the same
158 volume as applied to the grass sample in the agitator test were spread at the bottom of a

159 beaker to allow pH and WEP to be measured at 24 hr without disturbing the sample used
160 in the agitator test.

161

162 **Agitator test**

163

164 Prior to the start of the agitator test, the intact soil samples were transferred into the
165 beakers. The depth of soil in the beakers ranged from 40 mm to 50 mm; this was
166 considered sufficient to include the full depth of influence (Mulqueen et al., 2004).

167

168 The agitator test comprised 10 different treatments: a grassed sod-only treatment (the
169 study control); grassed sod receiving dairy cattle slurry at a rate equivalent to 40 kg
170 TP/ha, and grassed soil receiving 8 different chemically treated slurries (Table 1) applied
171 at a rate equivalent to 40 kg TP/ha. Each of the 8 amendments were applied at 3 different
172 rates (high, medium and low) in triplicate (n=3). The chemically amended slurry was
173 initially applied to the soil (t=0 hr), and was then allowed to interact for 24 hr prior to
174 saturation of the sample. After 24 hr (t=24 hr), samples were saturated by gently adding
175 deionised water to the soil sample at intermittent time intervals until water pooled on the
176 surface. The sample was saturated for 24 hr (t=48 hr). Immediately after saturation was
177 complete, 500 ml of deionised water was added to the beaker. The agitator paddle was
178 then lowered to mid-depth in the overlying water and rotated at 20 rpm for 24 hr.

179

180 **Water sampling and analysis**

181

182 Water samples (4 ml) were taken at 0.25, 0.5, 1, 2, 4, 8, 12 and 24 hr after the start of the
183 test. All samples were filtered immediately after sample collection using 0.45 µm filters
184 and placed in a freezer (after APHA, 1995) prior to being analysed colorimetrically for
185 DRP using a nutrient analyser (Konelab 20, Thermo Clinical Labsystems, Finland). The
186 DRP concentrations were used to calculate the mass of DRP in the water overlying the
187 soil samples in the beaker, taking into account the water volume reduction as the test
188 progressed. All water samples were tested in accordance with standard methods (APHA,
189 1995).

190

191 **Statistical Analysis**

192

193 The results were analysed using SAS (SAS Institute, 2004). Proc Mixed was used to
194 model the factorial structures (amendment x application rate; and amendment x
195 application rate x time) in the experiment in order to allow for heterogeneous variance
196 across treatments. A group variable was fitted to allow comparisons between the control
197 treatments and the factorial combinations. A multiple comparisons procedure (Tukey)
198 was used to compare means.

199

200 **Results and Discussion**

201

202 **Soil analysis results**

203

204 The soil used in this study had a M3-P concentration of 107 ± 2.8 mg P/kg, Morgan's P
205 concentration of 12.3 ± 0.49 mg/L and a soil pH of 5.6 ± 0.1 . The SMP buffer pH of the
206 soil was 6.1 ± 0.2 and the LR was calculated to be 9.9 ± 1 t/ha. The soil used in this study
207 comprised 15% gravel, 72% sand, and 13% fines, and had an organic matter content of
208 $16.2 \pm 0.2\%$.

209

210 **Slurry and by-product analyses**

211

212 Slurry used had TN of 3982 ± 274 mg/L, TP of 803 ± 37 mg/L, TK of 4009 ± 482 and pH of
213 7.3 ± 0.1 . Slurry WEP values at 24 hr are tabulated in Table 1.

214

215 Table 2 shows the properties of the PSMs used in this study, the load of metals per
216 hectare for optimum treatment, the maximum permissible annual average rates of addition
217 of certain heavy metals to mineral and organic soils over a 10-yr period, and the limits on
218 metal concentrations for potable water abstraction.

219

220 In a 20-yr plot study, Moore and Edwards (2005) found that after 10 yr, exchangeable Al
221 was lower in plots fertilized with untreated litter and alum-treated litter than in plots
222 receiving NH_4NO_3 . Soil pH, and not the total Al content, controls Al availability.

223 Therefore, repeated alum treatment will not lead to an increase in Al availability.

224

225

226 **Effectiveness of chemical amendments and PSMs in reducing DRP in overlying**
227 **water.**

228

229 The overall statistical analysis showed that there was a significant interaction between
230 treatment and application rate, but that the interaction effects were small compared to the
231 main effects. Comparisons of means were made from the interaction table. Figure 1
232 shows the mass of DRP in the water overlying the untreated soil and slurry-only
233 treatments in the agitator tests. The reductions in mass of DRP in the overlying water for
234 each amendment at 3 rates are tabulated in Table 1. Effervescence did not occur at the
235 lower application rates. However, slurry volume increased by approximately 50% when
236 alum was applied at 2.44 Al:TP. Lefcourt and Meisinger (2001) reported similar results,
237 recommending that alum be added slowly. The addition of $AlCl_3$ increased the difficulty
238 of handling the slurry compared to the alum treatment, due to formation of foam on the
239 surface of the slurry. This phenomenon was also noted by Smith et al. (2001b). $FeCl_2$ was
240 very effective and these results were in agreement with Moore and Miller (1994).

241 However, it was not as efficient as alum or $AlCl_3$ treatments. Lime was less effective
242 than Fe and Al-based compounds.

243

244 In this study, Al-WTR-1 reduced soluble P in water overlying the soil by 31%, 77% and
245 74% when applied at rates of 0.28, 0.69, and 1.4 kg of dry matter of sludge/kg of dry
246 matter of dairy cattle slurry, respectively (0.28 kg/kg versus 1.4 kg/kg rates, $p=0.003$, no
247 significant difference between the 0.69 kg/kg and 1.4 kg/kg rates). Homogenised Al-
248 WTR-2 reduced soluble P in water overlying the soil by 0%, 71% and 67%, when applied

249 on an equivalent basis. While not statistically significant, the irregularity between the
250 0.69 and 1.4 kg/kg treatment rates was found to be consistent across sieved and sludge
251 treatments. McGrath et al. (2010) observed a 91% reduction in soluble P at when Al-
252 WTR was applied at 0.2 kg/kg. The WTR used by McGrath et al. (2010) had Fe of 3.1%
253 and Al of 7.6% - higher than the composition of WTR used in this study.

254

255 Flyash and FGD reduced soluble P in cattle slurry by 72% (versus control, $p<0.0001$) and
256 89% (versus control, $p<0.0001$), respectively, when applied at 4.2 kg/kg and 5.6 kg/kg,
257 respectively. These rates of addition are higher than those used in previous studies (Dao,
258 1999; Dou et al., 2003).

259

260 Statistical analysis found that there was evidence of a three-way interaction between
261 amendment, rate of application and time, but that the interaction was on a smaller scale
262 than the main effects of amendment and time. Initially, the pH of the slurry was 7.3 ± 0.5
263 ($p<0.0001$); the acidifying additives increase acidity of the slurry. Meisinger et al. (2001)
264 found that pH would need to be lower than 5 to significantly reduce gaseous emissions.
265 Lime addition increased the pH to a maximum value of 8.8 ($p<0.0001$). Application of
266 Al-WTR, flyash and FGD did not significantly alter slurry pH initially.

267

268 At $t=24$ hr, slurry pH increased to 7.8 ($p<0.0001$), while the effects of the acidifying
269 additives reduced. Lime-treated slurry pH increased to 10.3 ($p<0.0001$). The pH of Al-
270 WTR, flyash and FGD treatments also increased. Flyash had a pH of 9.3 ($p<0.0001$) at
271 the optimum application rate. The pH of the overlying water was not measured.

272

273 McGrath et al. (2010) demonstrated that Ca and Mg-rich PSMs were most effective at P
274 precipitation when manures or solution have sufficient buffering capacity to maintain a
275 pH of between 6.5 and 7.5, and that Fe and Al-based compounds were more effective at
276 low pH. This was consistent with the study findings.

277

278 **Cost analysis of all treatments**

279

280 The cost of each treatment per cubic metre of slurry and for a 100-livestock unit farm is
281 shown in Table 1. The cost of chemical amendment was calculated based on the
282 estimated cost of chemical, chemical delivery, addition of chemical to slurry, increases in
283 slurry agitation, and slurry spreading costs as a result of increased volume of slurry as a
284 consequence of adding amendments.

285

286 Figure 2 shows the total cost of chemical amendment of dairy cattle slurry, including
287 spreading and agitation costs, plotted against the potential reduction in DRP lost to
288 overlying water and the percentage reduction in DRP release to overlying water.

289

290 **Conclusions**

291

292 The findings of this study are:

293 (1) Alum is the most cost-effective chemical amendment capable of greater than 90%
294 reduction in soluble P in overlying water at an additional cost of €4.40/m³ slurry;

295 (2) FeCl_2 is the second most cost-effective chemical amendment with an 88% reduction
296 in soluble P in overlying water at an additional cost of €3.60/m³ slurry;
297 (3) AlCl_3 (€6.40/m³) and lime (€5.90/m³ slurry additional cost) applied at rates used in
298 this study, are expensive compared to alum and FeCl_2 and alum;
299 (4) Ca-based compounds ($\text{Ca}(\text{OH})_2$ and FGD) are much less effective at removing P than
300 Fe and Ca compounds. This due to the inability of slurry to buffer the pH of slurry
301 sufficiently to optimise Ca-P bond formation;
302 (5) Flyash results in a 72% reduction in DRP in the overlying water (€5.90/m³ slurry
303 additional cost).
304 (6) Alum-based drinking water treatment residuals reduce the loss of soluble P from dairy
305 cattle slurry by 71% at €1.20/m³ slurry additional cost, provided that the farmer has
306 additional storage facilities. In addition, Al and Fe-rich WTRs may be more effective at
307 lower application rates.
308 (7) Further work is necessary to prove that there is no risk to water quality associated
309 with these treatments.

310

311

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313

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478 **Captions for Tables**

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480 Table 1. Table showing cost of supply, delivery and addition of amendments, and
481 increase in agitation costs and spreading costs due to increases in volume^a and WEP of
482 slurry 24 hr after application.

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484 Table 2. Characterisation of PSMs used in the agitator test (mean \pm standard deviation)
485 tests carried out in triplicate, the maximum load of metals per hectare per treatment,
486 maximum permissible annual average rates of addition of certain heavy metals to soils
487 over a 10-yr period, background levels of these metals in mineral and organic soils, and
488 limits on heavy metal concentrations in water drinking water extraction.

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Table 1. Table showing cost of supply, delivery and addition of amendments, and increase in agitation costs and spreading costs due to increases in volume^a and WEP of slurry at 24hr.

Chemical ^b	Rate of addition	Cost ^c €/tonne	Rate kg/m ³	Spreading ^d €/m ³	Agitation ^e €/m ³	Cost water ^f €/m ³	Total €/m ³	100 unit farm €/farm	P reduction % P	Metals ⁱ kg/ha	WEP ^j mg/kg
None				1.6	0.50	0	2.1	1,240			2.64± 0.15
Alum	0.98:1 Al: P	150	23	1.6	0.51	0	5.6	3,310	83	49	0.51± 0.01
	1.22:1 Al: P		29	1.6	0.51	0	6.5	3,840	94	61	0.27± 0.07
	2.44:1 Al: P		58	1.6	0.53	0	10.9	6,470	99	122	0.03± 0.0
AlCl ₃ (PAC)	0.98:1 Al: P	280	18	1.6	0.51	0	7.2	4,300	87	49	2.08± 0.06
	1.22:1 Al: P		23	1.6	0.51	0	8.5	5,070	92	61	1.43± 0.02
	2.44:1 Al: P		46	1.6	0.52	0	15	8,930	99	122	0.16± 0.02
FeCl ₂ (FeCl ₃)	2:1 Fe: P	250	14	1.6	0.51	0	5.7	3,370	88	100	2.43± 0.27
	5:1 Fe: P		36	1.6	0.52	0	11.1	6,600	90	250	0.73± 0.06
	10:1 Fe: P		72	1.7	0.54	0	20.2	11,100	99	500	0.4± 0.02
Ca(OH) ₂	1:1 Ca: P	312	2	1.6	0.50	0	2.6	1,570	0	50	1.7± 0.06
	5:1 Ca: P		9	1.6	0.50	0	5	2,990	74	250	0.2± 0.02
	10:1 Ca: P		19	1.6	0.51	0	8	4,760	81	500	0.05± 0.0
<i>PSMs</i>											
Al-WTR-1	0.28 kg/kg	0	20	1.6	0.51	0	2.1	1,240	31		2.49± 0.06
(<2mm) ^g	0.69 kg/kg		50	1.9	0.61	0.3	2.8	1,670	77		1.73± 0.02
	1.4 kg/kg		100	2.6	0.83	1.1	4.5	2,680	74		0.93± 0.02
Al-WTR-2	0.28 kg/kg	5	63	1.6	0.53	0.3	2.5	1,480	0		1.13± 0.05
(sludge) ^h	0.69 kg/kg		156	1.9	0.61	0.8	3.4	2,010	71		0.28± 0.01
	1.4 kg/kg		313	2.5	0.81	1.6	5.5	3,270	67		0.07± 0.0
Flyash	2.1 kg/kg	14	150	3.2	1.04	1.8	8.2	4,850	43		0.92± 0.14
	4.2 kg/kg		300	4.9	1.58	3.6	14.3	8,480	72		0.21± 0.08
	5.6 kg/kg		400	5.8	1.89	4.6	17.9	10,600	91		0.22± 0.04
FDG ^g	1.33 kg/kg	14	150	2.5	0.81	0.9	6.3	3,740	72		0.09± 0.0
	2.65 kg/kg		300	3.6	1.17	2	11	6,520	89		0.05± 0.0
	3.5 kg/kg		400	4.3	1.37	2.6	13.8	8,210	81		0.04± 0.0

^a These calculations are based a dairy farm with 100 cows, or equivalent stock, with a 18-wk winter. Sample slurry properties are based on based average values from this study (TP = 811 mg/L, density of 1.01 g/cm³ and dry matter content of 7.2%).

^b Ca(OH)₂, AlCl₃ (PAC) and FeCl₂ (FeCl₃) were laboratory chemicals; the most similar product on the market (in brackets) was chosen for cost estimates.

^c Total cost of material, delivery of material and addition of material to slurry in slurry storage tank per cubic meter of amendment used.

^d Slurry spreading costs estimated based on data from Teagasc (S. Lawlor *pers comm*, 2010) and increase in volume of slurry due to amendment.

^eSlurry agitating costs estimated based on data from Teagasc (2008) with and increase in volume of slurry due to amendment.

^fFor ease of handling water DM must be approximately 10%. Some amendments resulted in DM >10%. Water would need to be added to the slurry to enable spreading.

^gAl-WTR-1 <2 mm is alum-based water treatment residual which has been dried and crushed to pass the 2mm sieve

^hAl-WTR-2 sludge is the homogenised alum-based water treatment residual in its natural state after water treatment and separation.

ⁱTotal metal applied for each of the chemical amendments was calculated based on a slurry application rate of 50 m³/ha for each treatment. ^jWEP of slurry 24 hr after start of agitator test.

Table 2. Characterisation of PSMs used in the agitator test (mean \pm standard deviation) tests carried out in triplicate, the maximum load of metals per hectare per treatment, maximum permissible annual average rates of addition of certain heavy metals to soils over a 10 year period and background levels of these metals in mineral and organic soils and limits on heavy metal concentrations in water drinking water extraction.

Parameter		By-product characterisation				Metal application rate ^a				Application Background ^d			Water
Unit		Al-WTR-1	Al-WTR-2	Flyash	FGD ^b	Al-WTR-1	Al-WTR-2	Flyash	FGD	limits ^c	Mineral soil	Organic soil	limits ^e
		(<2mm)	(Sludge)			kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	mg/L
DM	%	100	32 \pm 2	99.9 \pm 0.01	37 \pm 3								
pH		7.9 \pm 0.1	6.9 \pm 0.2	11.2 \pm 0.04	8.6 \pm 0.01								
WEP	mg/kg	<0.01		<0.01	<0.01	280	420	848	6.75				
Al	%	11.1 \pm 0.05	5.33 \pm 1.2	5.66 \pm 0.2	0.09 \pm 0.0	0.02	0.02	0.2	0		97,000	70,000	0.05
As	mg/kg	6.2 \pm 1.1	<0.01	13.3 \pm 0.6	<0.01	32.4	8.6	730	1520		31.5	26.7	
Ca	%	1.3 \pm 0.08	0.11 \pm 0.0	4.85 \pm 0.2	20 \pm 0.3	0.0004	0	0.009	0.0013		36,300	39,900	
Cd	mg/kg	0.16 \pm 0.03	<0.01	0.58 \pm 0.03	0.17 \pm 0.02	0.0012	0	0.5	0.0025	0.05	2.31	2.23	0.005
Co	mg/kg	0.49 \pm 0.28	<0.01	33.3 \pm 1.2	0.3 \pm 0.14	0.01	0.0024	1.33	0.0225		21.7	16.7	
Cr	mg/kg	3.8 \pm 0.21	0.3 \pm 0.02	88.3 \pm 1.5	3 \pm 0.1	0.08	0.005	0.49	0.28	3.5	126	74.9	
Cu	mg/kg	31.7 \pm 1.5	0.63 \pm 0.03	32.7 \pm 1.5	37 \pm 13	61	0.8	320	4.5	7.5	64.5	57.5	
Fe	%	0.24 \pm 0.01	0.01 \pm 0.0	2.15 \pm 0.1	0.06 \pm 0.01	0.67	0	15	2.25		52,300	49,800	
K	%	0.03 \pm 0.01	<0.01	0.1	0.03	0.41	0.025	183	22.2		26,600	18,600	0.05
Mg	mg/kg	165 \pm 33	3.17 \pm 1.7	12200 \pm 610	2950 \pm 58	0.2	0.05	5.2	0.325		12,200	6,160	0.3
Mn	mg/kg	79 \pm 1	6.87 \pm 0.1	347 \pm 160	31 \pm 0.6	0.001	0	0.12	0.006		2,780	2,050	
Mo	mg/kg	0.47 \pm 0.2	<0.01	7.67 \pm 0.5	0.73 \pm 0.3	15	0.51	20.5	4.95		4.6	4.73	0.05*
Na	mg/kg	611 \pm 180	65 \pm 14	1370 \pm 610	660 \pm 93	0.012	0.005	0.67	0.09	3	15,800	10,200	
Ni	mg/kg	4.8 \pm 0.06	0.6 \pm 0.2	44 \pm 1	11 \pm 0.6	0.6	0.15	81.9	0.49		72.7	49.6	
TP	mg/kg	234 \pm 5.3	18.7 \pm 1.6	5460 \pm 630	65 \pm 21	0.003	0	0.45	0.006	4	2,800	2,660	0.4*
Pb	mg/kg	1.2 \pm 0.8	<0.01	30 \pm 1.7	0.74 \pm 0.4	0.008	0.0016	2.32	0.37		85.4	81.3	0.05
V	mg/kg	3 \pm 0.2	0.2 \pm 0.01	155 \pm 3.6	49 \pm 2	0.043	0.006	1.13	0.07	7.5	152	105	0.5*
Zn	mg/kg	17 \pm 0	0.8 \pm 0.1	75 \pm 3.1	9.4 \pm 2						210	139	

^aThe maximum load of each metal per hectare for each treatment is tabulated based on a slurry application rate of 50m³/ha and the optimum rate for each amendment. ^bFGD is flue gas desulphurisation product.

^cGuideline limits in the Code of Good Practise for the use of biosolids in agriculture (Timoney, 2009) for the max permissible annual average rates of addition over a 10 year period.

^dTotal metal and nutrient concentrations (95% percentile) of soil (Soil Geochemical Atlas of Ireland (Fay et al., 2010)) in upper 100mm of soil (bulk density 1.4 g/cm³).

^eCharacteristics of surface water intended for the abstraction of drinking water (74/440/EEC), guidelines (*) where no mandatory limit.

Captions for figures.

Figure 1. Phosphorus released per unit surface area and DRP concentration in overlying water plotted against square root of time for undisturbed intact grassed sod only treatment () and grassed soil amended with slurry at () .

Figure 2. Total cost of chemical amendment of dairy cattle slurry including spreading and agitation costs plotted against the reduction in DRP lost to overlying water and the percentage reduction in DRP release to overlying water.

Figure 1.

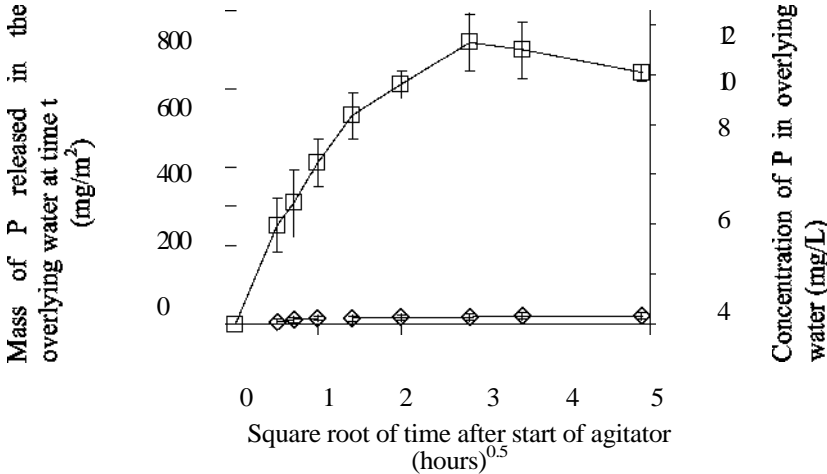
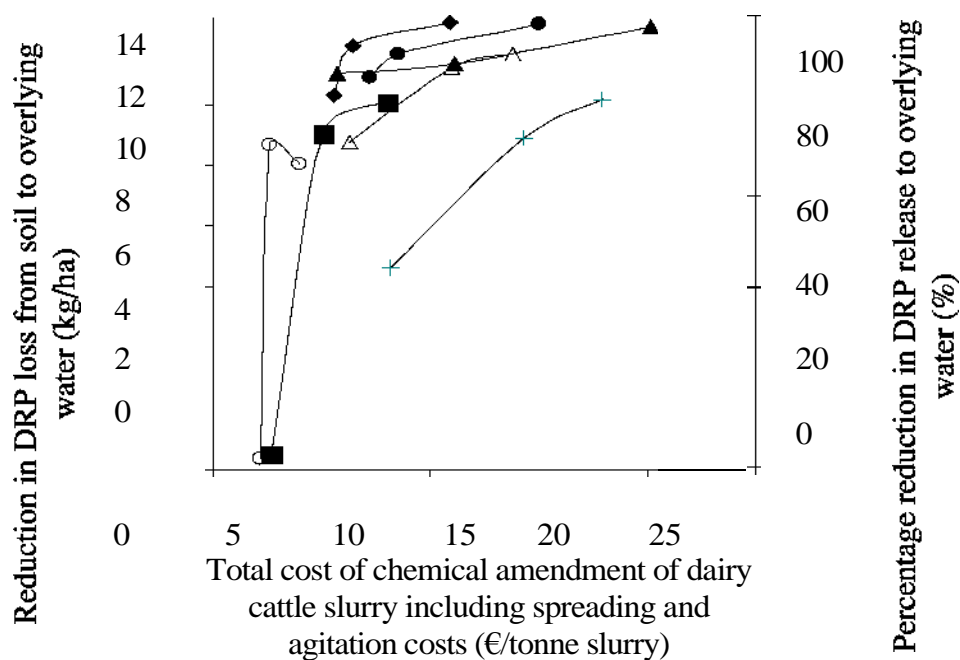


Figure 2.



Note:

The amendments plotted (each at three rates) are ♦ aluminium sulphate, ● aluminium chloride, ▲ ferric chloride, ■ burnt lime, ○ Al-WTR, + flyash and △ FGD.